Characteristics of Monitor for Laser Welding

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Process Monitor for Laser Beam Welding

Description and Operation

This patent-pending robust on-line weld process monitor developed by Argonne National Laboratory is capable of non-intrusively sensing weld surface changes, weld penetration, occurrence of weld spatter, direction of motion of workpiece relative to cover gas flow, and presence of surface impurities like oil on the workpiece. The development of the weld monitor took into account the constraints and operating environment of the factory floor in addition to monitoring needs for quality assurance. The non-intrusive weld monitor is rugged and simple to use, does not require power to operate, is weld spatter protected and low cost.

This process monitor is available as a stand-alone monitor with laser pointing suitable as an inexpensive addition to an existing processing system. For constrained configurations, the monitor can be easily integrated into an existing optic module resulting in through-the-optic viewing.

The stand-alone monitor's flexibility is suitable for test and evaluation or research and development applications where flexibility in pointing or change in optics is required. A photograph of the monitor is shown in Figure 1. The reproducibility of the monitor's signal output will depend on the accuracy and repeatability in aiming. Laser aiming that comes with the monitor offers the best overall accuracy and ease. Costs can be reduced further with conventional gunsights with loss in accuracy and ease. The reproducibility of the monitor's output will depend on the field of view, the aiming method and the capability to manually aim and lock in position. In practice, even with laser aiming, the accuracy will be compromised by the mechanical system used to allow for aiming adjustments. 10 to 20% changes may be result from using a flexible connector. Improved reproducibility can be obtained at the expense of time taken to aim accurately.

The integrated version of the monitor is recommended for process operations. This integrated monitor is available as an option on Spawr Industries reflective optics for high power laser beams or as a modification to the user's beam delivery optics. The advantage of the integrated design is that the monitor is pre-aimed and does not suffer from bumping and space constraints. Excellent reproducibility of the data can then be obtained.

Both versions of the monitor are supplied with a BNC connector for detecting the voltage output of the sensor. The standard sensor is optimized for the monitoring of ferrous or steel alloys and other metals that have similar properties. Sensitivity to changes in penetration of < 0.05 mm can be expected. Monitoring of aluminum alloys will require a different sensor that is available as an option. A gas connection is also supplied for the clean gas purge to maintain the cleanliness of the window of the sensor. The gas (air or nitrogen) supplied should be oil and particle free to prevent fogging of the detector window.

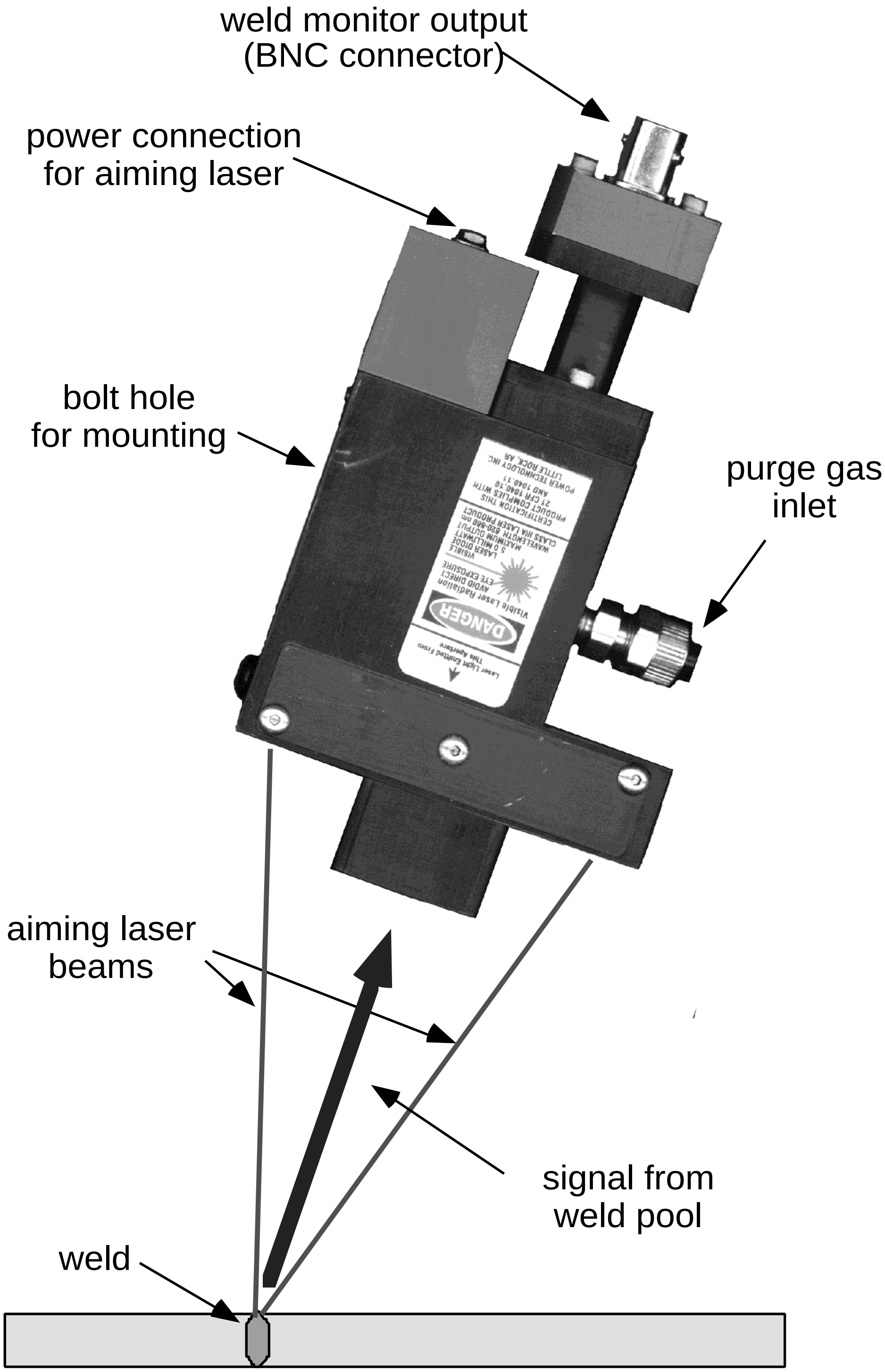

Figure 1. Annotated photograph of the stand-alone weld monitor with laser aiming. The purposes of the various connectors are indicated.

Principles of Monitoring

Fluctuations of the laser beam, plasma or acoustic emissions may indicate potential changes in the weld quality but monitoring of these secondary parameters or signals tend to be complex and difficult or expensive to implement. In addition, secondary signals are indirect indications of weld quality and the potential for tagging good welds as bad may be significant.

Argonne's weld monitoring concept focusses on the primary (direct) signals from the weld pool. Changes in the weld surface produce the AC component of the weld monitor signal and the weld penetration is indicated by the DC level of the signal. The degree and frequency of surface defects is reflected in the amplitude and frequency of the AC component of the weld monitor output. The presence of a significant AC component indicates that the weld surface is changing along the weld. For example, the weld monitor output will have an AC component that corresponds to the amplitude and frequency of the humping. The presence of a small (relative to the DC component) amplitude high frequency (>100 Hz) AC component indicates that the weld was made counter to the direction of the cover gas flow. The absence of this AC component indicates that the weld was made in the same direction as the cover gas flow. The presence of a substantial high frequency AC component is usually caused by the presence of surface impurity such as oil or the occurrence of spatter. Significant variation of the DC component corresponds to change in the penetration. The sensitivity will be limited by the reproducibility of the process, aiming and the noise level of the data acquisition system used to acquire the signal from the monitor. The magnitudes of both the AC and DC components of the signal are a function of the particular geometry of the welding application. Consequently, a calibration or characteristic weld monitor output signal is required for each application for quantitative determination although the qualitative nature of the signal for each type of defect or problem does not change.

An example of the weld monitor response to simulated defects is shown in Figure 2. The digital scan of the surface of the weld shown is for a lap weld of two sections of two 0.8 mm thick sheets of aluminum bearing stainless steel that have been butted together and shimmed on the right side. The steady DC component on the left indicated the full penetration of the weld until the position of the edge of the first sheet. The imprecision of the butting lead to some dropout of the weld and the substantial drop in the DC component. The DC component regained the previous level for the normal full penetration weld until the position where the shimming caused a large air gap between the sheets causing a decrease in the DC component. As the weld progressed, the shimming elevated the surface of the top sheet. This decreased the irradiance of the beam on the surface and resulted in lower penetration and lower DC component. The small AC component that is present for the entire signal was caused by the use of cover gas blowing in the opposite direction of the part motion. This configuration of cover gas deployment encourages plasma formation ahead of the weld. Use of cover gas blowing in the direction of part motion eliminates or reduces the plasma ahead of the weld and the AC component.

The correlation of the weld monitor signal to the penetration obtained for lap and bead-on-plate welds on a steel alloy is shown in Figure 3. The data was obtained by effecting linear welds at different power levels using a CO_2 beam (near TEM_{20}) and a Spawr focusing module. The monitor signals are correlated with the penetration obtained for each power level by sectioning each weld at one position only halfway along the length of the weld. The accuracy of the data from the stand-alone monitor was affected by the reproducibility in the aiming (on different days) and statistical variations from taking only one section from each weld. The preset aiming of the integrated monitor in the Spawr focus module resulted in improved correlation. Tests carried out with partial penetration welds on automotive components also resulted in linear correlations. The different workpieces and geometries produced different linear responses. Hence, calibration tests have to be carried out to determine the sensitivity or slope of each response for monitoring of the absolute change in penetration.

The output signals for a representative weld from the stand-alone and integrated versions of the weld monitor are shown in Figure 4. The data are selected from the welds described in Fig. 3. Figure 4 illustrates the difference in the AC portion of the signals resulting from the different relative movement of the workpiece in relation to the direction of the cover gas flow. Forming the weld in the same direction as the gas flow results in the substantial reduction in the AC component of the weld monitor signal. The tail of both signals should be ignored as they are generated after the part motion and beam had been terminated.

The effect of an oil layer on a steel part is illustrated in Figure 5. A layer of carbon was deposited around the welded area. The weld monitor signal was from a circular weld with overlap. The presence of the oil layer resulted in a substantial high frequency AC component. The amplitude of the AC component decreased for the overlap region because of the vaporization and pyrolysis of the oil from the prior laser beam interaction.

Data Acquisition and Analysis

The signal from the weld monitor consists of a DC voltage modulated by an AC component. The magnitude and frequency of the changes in the signal indicate the degree and rate of change in penetration or surface defects. Commercial hardware and software packages are available for data acquisition and analysis. The software applications available frequently have a variety of built in routines that enable easy retrieval of statistics such as mean and standard deviations and fast Fourier transforms for waveform analysis.

An example R & D application is the determination of a calibration curve for the monitoring of weld penetration. For the particular component under research, welds would be produced at different powers at a prescribed speed. The welds would then be sectioned and analyzed to quantify the penetration. A standard correlation can then be obtained for the weld monitor DC signal level. Based on the engineering design specifications, this correlation can be used to set upper and lower control limits to determine whether the weld is good or bad.

For process monitoring or control, a calibration curve may be difficult or costly to obtain particularly when it result in downtime for the production line. An alternative is to use statistical methods. Weld monitor signals for a statistically significant number of welds can be retrieved. As part of the ongoing statistical process control in effect, this batch of welds can be determined as statistically representative of welds that passes some prescribed strength tests. The data acquisition sytem software can then generate the signal trace envelope for the weld that will produce good welds. Each weld signal can then be compared to this statistical signal trace envelope to pass as a good weld.

The key features of the implementation of the weld monitor for process control are illustrated in Figure 6. The weld monitor output is amplified by isolation amplifiers, which provide both electrical isolation of the data acquisition system and raise the weld monitor signal from several hundred millivolts to a few volts, thus improving the noise immunity of the system. We have also isolated all other trigger and laser monitoring inputs to provide protection against ground loops. The data acquisition system compares the signal to predetermined control limits, based on statistical methods or design parameters, as discussed above. The weld monitor software then determines whether the part is good or potentially bad and passes that information to the CNC as a pass/fail signal.

Regardless of the method used for determining weld quality, a turnkey system is usually preferred for the manufacturing environment. In other words, the data acquisition and the determination of a potentially bad weld needs to be integrated into the computer numeric control such that defects can be tagged accordingly. Other users, such as R&D facilities or job shops, may prefer a more customized system.

To summarize, the user has three options for implementing the weld monitor:

(1) Purchase the weld monitor (stand-alone or integrated) and integrate it into the user's existing data acquisition hardware/softeware system using the general information supplied in this report.

(2) Purchase the weld monitor (stand-alone or integrated) and the application software. The user will still provide the computer and data acquisition hardware.

(3) Purchase a turn-key system, which will include the weld monitor hardware, software, and data acquisition system. Some final integration with the user's CNC controller will be required, depending upon customer preferences.

The weld monitor hardware is currently available, *i.e*., option (1) is currently viable. The current system was developed on a Macintosh hardware platform. For a Macintosh-based system, option (2) is also a current option. A cross-platform LabVIEW-based application is being developed to support various operating system and hardware preferences in a consistent fashion. The LabVIEW option also minimizes the effort required to support customization. Work is being initiated to develop a turn-key system and specify the proper industrial-grade computer, data acquisition, and connection components. It is expected that the same LabVIEW-based software will be used in a turn-key system with few, if any, additional modifications.

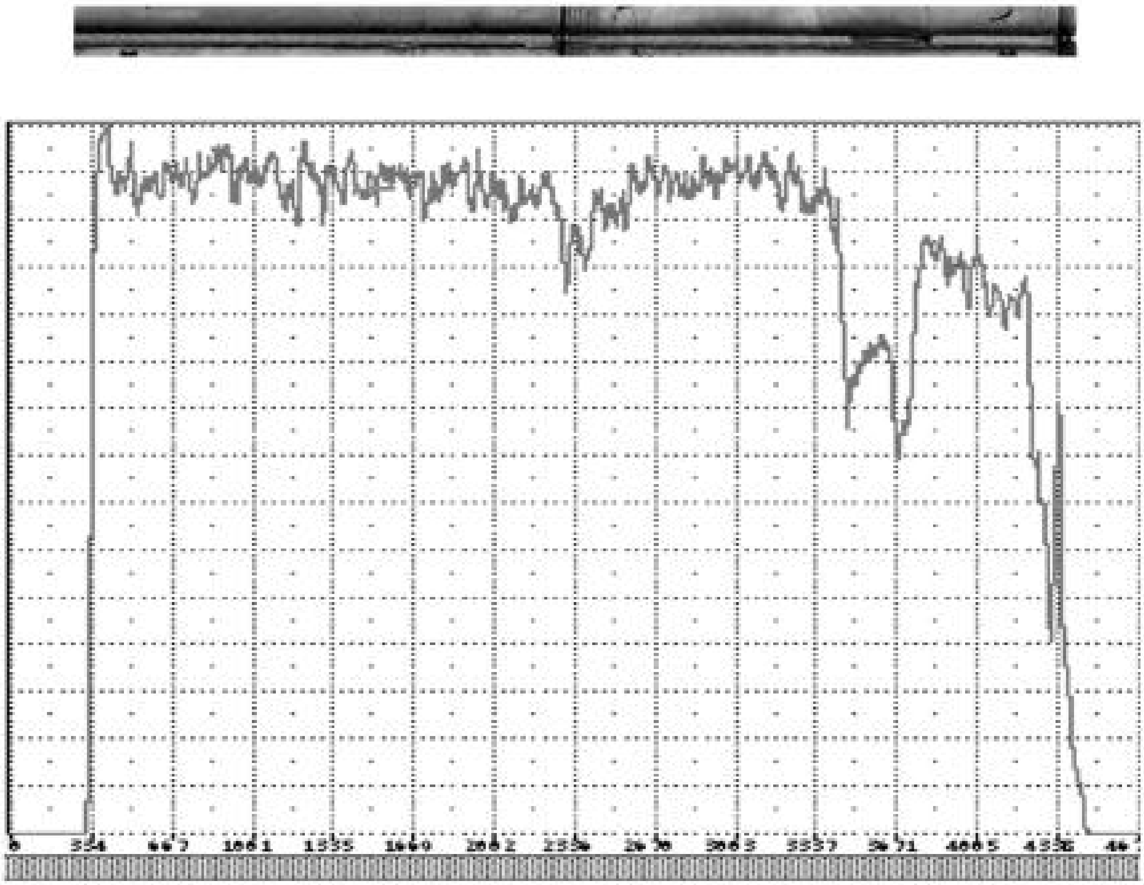

Figure 2. Weld monitor response to simulated defects in a lap weld. The surface of the the weld (top) shows the seam from butting the plates together. The corresponding response of the weld monitor to the gap and the drop out because of the air gap can be seen in the data trace (bottom).

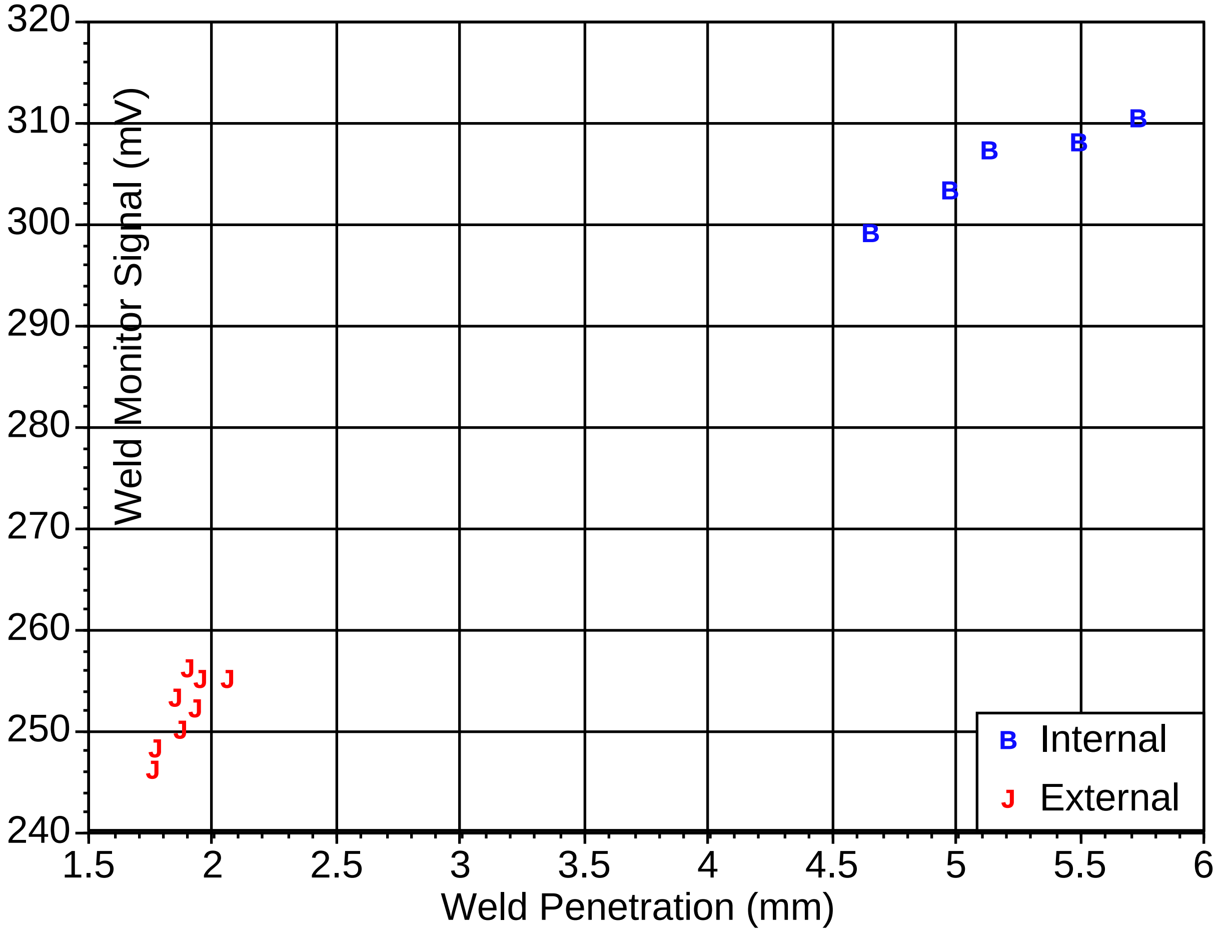

Figure 3. Weld monitor output from stand-alone and integrated weld monitors. The data from the stand alone monitor was generated using a 10” focal length lens and lap welds. The integrated monitor data was taken with an 8” focal length mirror and bead-on-plate welds.

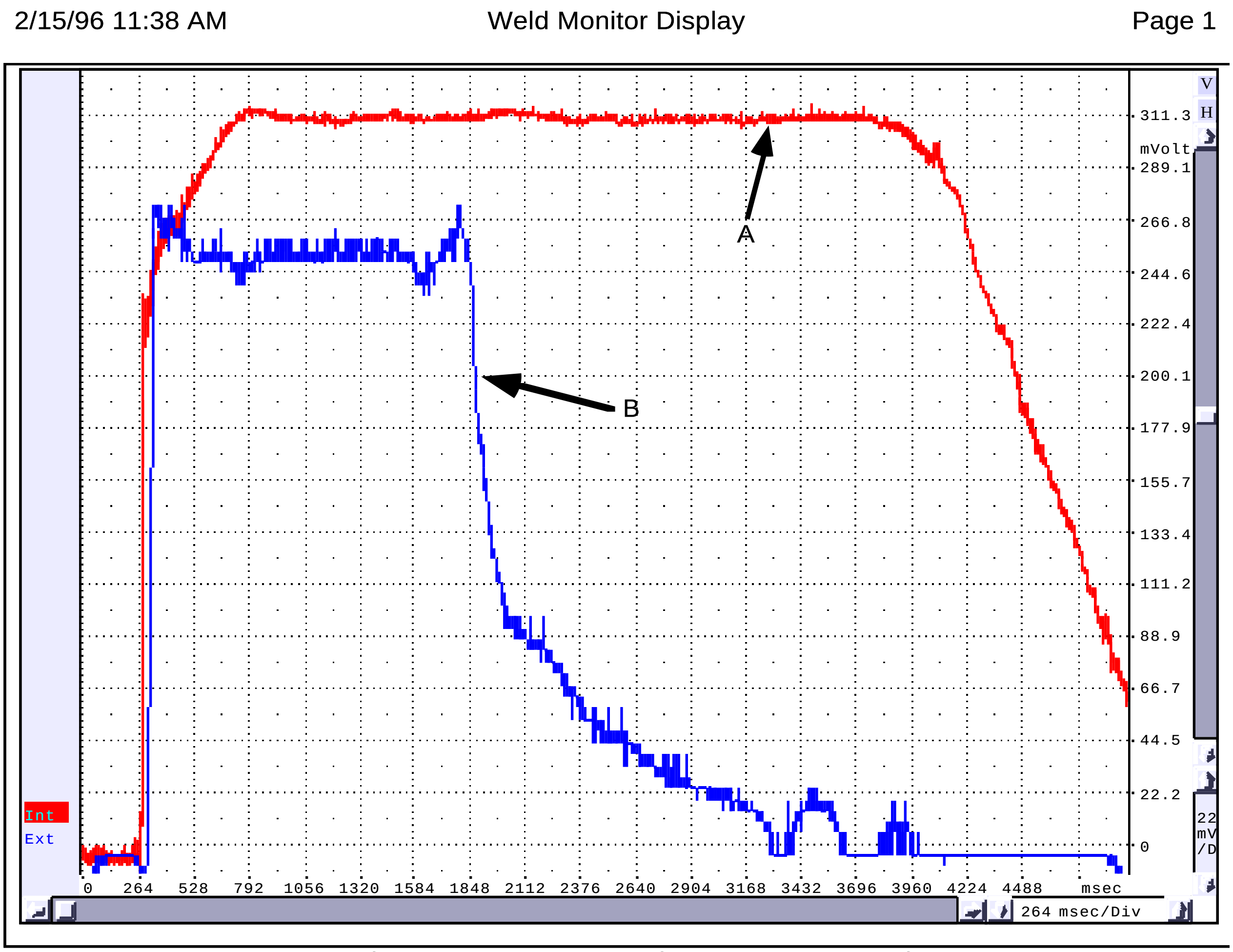

Figure 4. Comparison of weld monitor signals for using cover gas flow in the same direction as the part motion (A) and opposite (B). The signal (A) is from the integrated version of the weld monitor whereas (B) is from the stand-alone version. The different relative directions of cover gas flow resulted in the larger AC component in the stand-alone signal. The tails of the signals should be ignored as they were generated after part motion and beam had been terminated.

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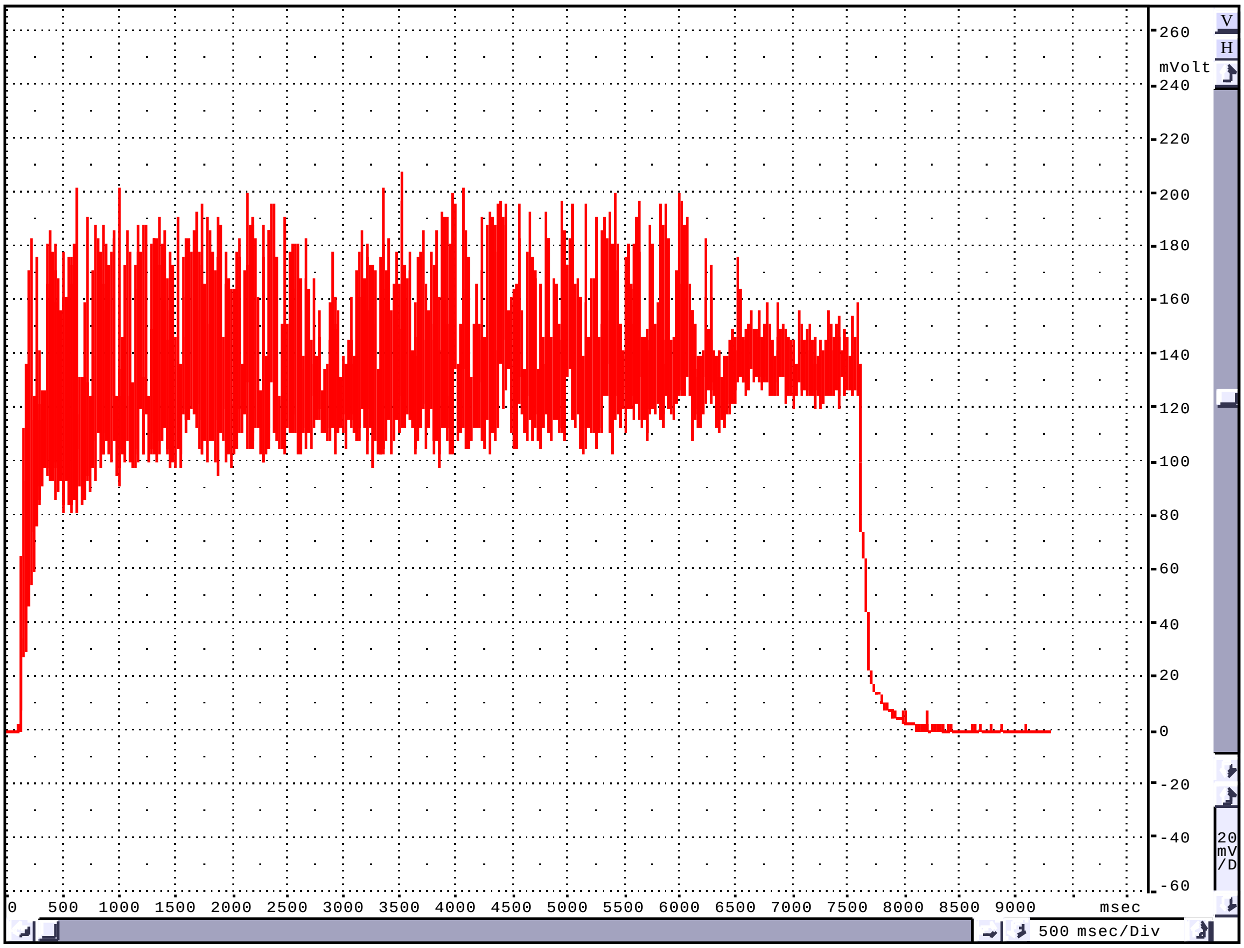

Figure 5. Weld monitor signal from an automotive component showing the effect of a surface contaminant (oil) on the signal. The sudden decrease in the AC component is due to the overlap in the weld.

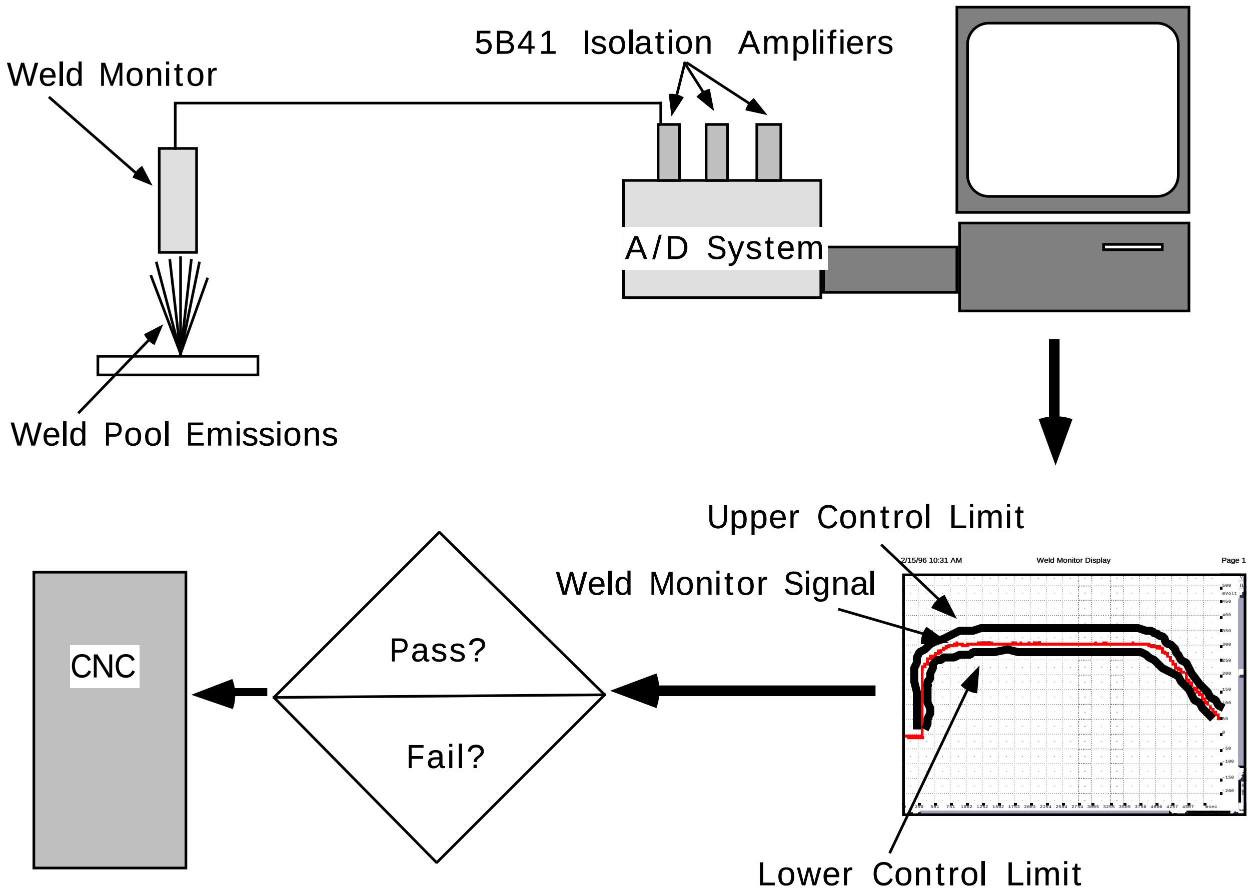

Figure 6. Schematic illustration of the key hardware and processing features required to use the weld monitor for process control.

Weld Monitor Specifications

remote sensing capabilities	**sensitivity/occurrence**
1. weld penetration	0.05 mm
2. weld surface features	humping undercut blow holes other surface changes
3. weld spatter	
4. surface contamination	oil film other impurities
5. direction of motion of workpiece relative to cover gas velocity	

monitor configurations

1. standalone with laser aiming
2. integrated into user's beam delivery optics

standard detector for welding of iron and steel alloys
optional detector for welding of aluminum or other alloys
BNC output connector standard, option for other connectors

power requirements

no power required for standard detector
110 VAC for operation of power supply for diode laser used in aiming